CLIMATE CHANGE IMPACTS ON LAURENTIAN GREAT LAKES LEVELS[1]

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Abstract. Scenarios of water supplies reflecting CO_2-induced climatic change are used to determine potential impacts on levels of the Laurentian Great Lakes and likely water management policy implications. The water supplies are based on conceptual models that link climate change scenarios from general circulation models to estimates of basin runoff, overlake precipitation, and lake evaporation. The water supply components are used in conjunction with operational regulation plans and hydraulic routing models of outlet and connecting channel flows to estimate water levels on Lakes Superior, Michigan, Huron, St. Clair, Erie, and Ontario. Three steady-state climate change scenarios, corresponding to modeling a doubling of atmospheric CO_2, are compared to a steady-state simulation obtained with historical data representing an unchanged atmosphere. One transient climate change scenario, representing a modeled transition from present conditions to doubled CO_2 concentrations, is compared to a transient simulation with historical data. The environmental, socioeconomic, and policy implications of the climate change effects modeled herein suggest that new paradigms in water management will be required to address the prospective increased allocation conflicts between users of the Great Lakes.

1. Introduction

The Great Lakes comprise one of the world's major freshwater resources. Containing approximately 23,000 km^3 of water, they represent about 20% of the world's fresh surface water. The lakes are also one of the most intensively used freshwater systems in the world, serving navigation, hydropower, irrigation, water supply, and recreation interests, while providing important fish and wildlife habitat. Present Great Lakes management strategies are largely based on net basin supplies, lake levels, and connecting channel flows experienced over the first 75 years of this century. Strategies based upon typical assumptions of climatic stationarity will likely prove inadequate if global warming due to increased atmospheric concentrations of CO_2 and other gases occurs as expected (Changnon, 1987). Expensive projects with long lifetimes (e.g., control structures, navigation locks, hydropower production facilities, shore protection works) can especially benefit from consideration of potential climate change impacts, even though those impacts are highly uncertain.

The U.S. Environmental Protection Agency (EPA), at the direction of the Congress, coordinated several regional studies of potential effects of a doubling of atmospheric CO_2 ($2 \times CO_2$) on various aspects of society, including agriculture,

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forestry, and water resources (EPA, 1988). As part of that study, Croley (1990) assessed steady-state and transient changes in Great Lakes net basin supplies consequent with simulated atmospheric scenarios from three general circulation models. Cohen (1986) has highlighted the need to extend Great Lakes climate change impact analyses to lake-level changes and potential consequences for the regional economy and environment. Marchand *et al.* (1988) reported lake-level changes based on Cohen's $2 \times CO_2$ water supply estimates; however, the supply estimates represent only a single atmospheric scenario and have important limitations as discussed by Croley (1990). This paper uses the hydrologic changes developed by Croley to determine impacts on Great Lakes levels and flows, and environmental, socioeconomic, and policy implications of the resulting changes in the Great Lakes system.

1.1. *The Physical System*

The Great Lakes system extends over 3200 km from the western edge of Lake Superior to the Moses-Saunders Power Dam on the St. Lawrence River. Over this distance, the water surface drops in a cascade from 182 m to sea level. The most upstream, largest, and deepest lake is Lake Superior. Lake Superior outflows are controlled according to Plan 1977, under the auspices of the International Joint Commission (IJC). The lake has two interbasin diversions of water into the system from the Hudson Bay basin: the Ogoki and Long Lac diversions. Lake Superior waters flow through the lock and compensating works at Sault Ste. Marie, Michigan and down the St. Marys River into Lake Huron where it is joined by water flowing from Lake Michigan.

Lakes Michigan and Huron are considered to be one lake hydraulically because of their connection through the deep Straits of Mackinac. The second interbasin diversion takes place from Lake Michigan at Chicago, Illinois. Here water is diverted from the Great Lakes to the Mississippi River basin. The water from Lake Huron flows through the St. Clair River, Lake St. Clair, and Detroit River system into Lake Erie. The drop in water surface between Lakes Michigan-Huron and Erie is only about 2.4 m. This results in a large backwater effect between Lakes Erie, St. Clair, and Michigan-Huron; changes in Lakes St. Clair and Erie levels are transmitted upstream to Lakes Michigan and Huron.

From Lake Erie the flow continues through the Niagara River and Welland Canal diversion into Lake Ontario. The 52 m drop over Niagara Falls precludes changes in Lake Ontario from being transmitted to the upstream lakes. The Welland Canal diversion is an intrabasin diversion bypassing Niagara Falls and is used for navigation and hydropower production. There is also a small diversion into the New York State Barge Canal system (too small to have a measurable effect on lake levels) which is ultimately discharged into Lake Ontario. Lake Ontario outflows are controlled in accordance with Plan 1958-D, also under the auspices of the IJC. From Lake Ontario, the water flows through the St. Lawrence River to the

Gulf of St. Lawrence and the Atlantic Ocean, passing through an important harbor at Montreal, Quebec.

The hydrologic cycle of the Great Lakes basin determines the lake levels. Net basin supplies typically reach a maximum in the late spring and a minimum in late fall. The imbalance between total water supplies (net basin supplies and inflows from any upstream lake) and outflows from a lake results in rising or falling levels. There are three primary types of fluctuations of Great Lakes levels: annual, seasonal, and short-term variations due to wind setup and storm surge. Annual fluctuations result in most of the variability leading to record high or low lake levels. There is an overall range of about 1.8 m in the annual levels. Superimposed on the annual levels are seasonal cycles, which range from about 0.38 m on Lake Ontario to about 0.30 m on Lake Michigan-Huron. In general, seasonal cycles have a minimum in the winter, usually January or February. The levels then rise due to increasing net basin supplies from snowmelt and spring precipitation until they reach a maximum in June for the smaller lakes (e.g., Erie and Ontario) or in September in the case of Lake Superior. The lakes begin their seasonal declines in the late summer and fall. The final type of fluctuation, storm surge or wind setup, is relatively short-lived, lasting only several hours. While sometimes large (Lake Erie has experienced differences between levels on the eastern and western ends of the lake as large as 4.9 m), they are too transitory to be considered by the model applications herein and are not discussed further.

1.2. *Study Approach*

The Great Lakes Environmental Research Laboratory (GLERL) received three $2 \times CO_2$ scenarios from the EPA expressed as ratios of 'future' to 'present' meteorology. They were obtained from three different general circulation models (GCMs) from the Goddard Institute for Space Studies, the Geophysical Fluid Dynamics Laboratory, and Oregon State University (referred to as the GISS, GFDL, and OSU scenarios, respectively). Croley (1990) applied these ratios to 30-year historic data sets for air temperatures, precipitation, humidity, wind speed, and cloud cover to estimate sequences of atmospheric conditions associated with a changed climate. He then used conceptual models to simulate runoff from the 121 subbasins draining into the Great Lakes, overlake precipitation into each lake, and evaporation from each lake. Each of the net basin supply components was modeled separately and then combined to estimate supplies to Lakes Superior, Michigan, Huron, St. Clair, Erie, and Ontario. These climate change scenarios were compared to a 'base case scenario' derived using the same models but with unmodified historic data sets.

To determine the impacts of changed net basin supplies on levels and flows throughout the entire Great Lakes system, operational regulation plans for Lakes Superior and Ontario were integrated with a hydraulic routing model for the unregulated lakes. The integrated models enabled a comparison between simulations based on changed net basin supplies (representing changed climates) and simulations based on net basin supplies derived from historic meteorology (representing an unchanged climate). For the steady-state scenarios, lake level simulations were repeated with initial lake levels set equal to their averages over the 30-year simulation until they were unchanging. For the transient-state scenario, initial lake levels were set to those actually occurring on 1 January, 1981.

Based on resulting changes in lake levels, qualitative impact scenarios are developed for various economic and environmental scenarios following Cohen's framework (1986). Croley (1990) discusses several assumptions and limitations inherent in his modeling of net basin supplies, including unchanged solar insolation, unchanged over-water and over-land atmospheric relationships, and averaging all meteorologic variables in the same manner. The approach used herein and by Croley does not enable consideration of changes in interannual variability or altered frequencies of extreme events. Thus, while this paper provides an idea of the general nature and direction of potential climate change impacts, it does not address how new extremes or frequencies of droughts, floods, heat spells, or cold snaps may affect the lakes and their use.

2. System Models

2.2. *Lake Superior Regulation*

Lake Superior outflows are determined by using Plan 1977 as implemented for simulation studies (International Lake Superior Board of Control, 1981, 1982), with modifications (discussed subsequently). Plan 1977 was designed to balance the levels of Lakes Superior and Michigan-Huron relative to their long-term average levels while considering their normal variability. It requires net basin supply estimates and initial water levels for Lakes Superior, Michigan-Huron, St. Clair, and Erie. For each month during May through November, the Lake Superior outflow structure gates are opened to the average setting required over the remainder of the period through November. Regulation over December through April is accomplished by setting the gate opening to the average required over the 5-month period and leaving it unchanged throughout.

For this study, a constant Long Lac diversion of 40 $m^3 s^{-1}$ is added to the net basin supplies each month for all scenarios. The Ogoki diversion, which averages about 119 $m^3 s^{-1}$, is implicitly included in the net basin supplies to Lake Superior; the diversion comprises part of the gaged river flows into Lake Superior and thus is included in the modeled basin runoff. In addition, net basin supplies are reduced by 7 $m^3 s^{-1}$ for all scenarios to reflect present consumptive water use estimates (International Great Lakes Diversions and Consumptive Uses Study Board, 1981).

2.3. *Hydraulic Routing*

Plan 1977 requires a hydraulic routing model for the connecting channels to determine projected water levels for Lake Michigan-Huron, which then affect the control of Lake Superior outflows. The routing model must consider net basin supplies, diversions, St. Marys River flows, and ice retardation of flows in the determination of water levels on Lakes Michigan-Huron, St. Clair, and Erie, and flows through the St. Clair, Detroit, and Niagara Rivers. Plan 1977 uses an iterative approach in level-pool routing to solve a series of stage-fall-discharge equations for each of the connecting channels and continuity for each lake. However, GLERL's Hydrologic Response Model (HRM) (Quinn, 1978; Hartmann, 1988), which uses the same reservoir routing concepts, uses discharge equations that better reflect present channel conditions, more appropriately relates lake storage changes to lake level fluctuations, and considers consumptive use rates (Hartmann, 1987). The HRM also uses a second-order finite-difference solution technique requiring 50 times fewer computations, offering significant advantages for studies requiring many simulations or for implementation on small computers. Hence, the hydraulic routing component of Plan 1977 used herein is the HRM.

The HRM was calibrated to determine discharge parameters that minimize errors between modeled and actual monthly lake levels over the calibration period, 1962–1980 (Hartmann, 1988). For this study, the HRM is updated to include a Niagara River discharge equation that reflects the changed flow regime resulting from landfills in the upper reaches of the channel that were completed in early 1973; the new equation is based on measured flows over 1974–1986 (Quinn, 1988). Table I shows statistics on use of the HRM over 1962–1980 using the new Niagara River equation. Although the updated HRM is thus strictly applicable only after the landfills, Table I shows that the model adequately simulates conditions in the unregulated portion of the Great Lakes even for earlier periods. The comparatively large modeled Niagara River flow errors reflect, in part, widely recognized uncertainties in 'actual' flow estimates of the same order of magnitude as the

TABLE I: Hydrologic response model application statistics, 1962–1980

	Mean monthly actual	Mean monthly model	Std. dev. actual	Std. dev. model	Root mean square error
Levels (m)					
Lake Michigan-Huron	176.34	176.35	0.43	0.44	0.02
Lake St. Clair	174.94	174.97	0.40	0.36	0.07
Lake Erie	174.06	174.10	0.37	0.34	0.05
Flows ($m^3 s^{-1}$)					
St. Clair River	5388	5383	640	640	62
Detroit River	5522	5531	630	639	73
Niagara River	5938	6020	774	767	151

modeling error of Table I (F. H. Quinn, GLERL, personal communication, 1988).

Application of the HRM for the present study requires several assumptions concerning diversions, consumptive use rates, and the ice retardation of flows in the connecting channels. Constant diversion rates of 91 and 261 $m^3 s^{-1}$ are used for the Chicago and Welland Canal diversions respectively. Consumptive use rates of 56 and 62 $m^3 s^{-1}$ are used for Lakes Michigan-Huron and Erie respectively (International Great Lakes Diversions and Consumptive Uses Study Board, 1981); no such estimates exist for Lake St. Clair. Long-term average rates of ice retardation of flows over 1937–1981 are used for the St. Clair and Detroit Rivers; estimates of ice effects on flows through those channels are not available for other periods. Although the climate change scenarios indicate that ice cover on the lakes will likely be significantly reduced, prospects still remain for ice retardation of flows in the connecting channels (Assel, 1988). No ice retardation is considered for the Niagara River, since the ice boom effectively eliminates ice jams on that river.

2.4. *Lake Ontario Regulation*

Lake Ontario levels and outflows are determined using Plan 1958-D (International St. Lawrence River Board of Control, 1963). The plan attempts to satisfy many, often conflicting, interests including riparian, hydropower, and shipping concerns both upstream and downstream of the lake outlet. Plan 1958-D first derives a basic regulated outflow, then applies a seasonal adjustment, and finally modifies the flows to comply with minimum and maximum outflow limitations. Simulations described herein use a consumptive use rate from the lake of 15 $m^3 s^{-1}$ (International Great Lakes Diversions and Consumptive Uses Study Board, 1981).

Plan 1958-D was designed to accommodate extended periods of above average water supplies, but it also allows for discretionary authority (i.e., ad hoc regulation) during extreme conditions. During the high water supply conditions of 1985 and 1986, discretionary authority was credited with reducing levels on Lake Ontario by 0.76 m, preventing record high lake levels (U.S. Army Corps of Engineers, 1987). Suitability of the plan for extended low water supplies is less certain; such conditions have not been experienced since the plan was developed.

2.5. *Model Applicability*

It is difficult to assess the applicability of the integrated models by comparing simulated and historical levels and flows over an extended period. The Great Lakes system has a long history of human manipulation, including dredging of the St. Clair and Detroit Rivers for mining gravel and improving navigation channels, landfilling and hydropower operations in the Niagara River channel, and the regulation of Lakes Superior and Ontario under a variety of regulation plans. Additionally, Lakes Superior and Ontario have each experienced discretionary regulation during extreme water supply conditions. Thus, any evaluation of the integrated

TABLE II: Comparison of historical and base case scenario lake levels and flows, 1973–1980

	Mean monthly actual	Mean monthly model	Std. dev. actual	Root mean square error	Corr.
Levels (m)					
Lake Superior	183.12	183.14	0.14	0.08	0.84
Lake Michigan-Huron[a]	176.63	176.54	0.24	0.15	0.87
Lake St. Clair	175.24	175.11	0.21	0.17	0.85
Lake Erie	174.33	174.18	0.23	0.19	0.89
Lake Ontario	74.78	74.72	0.28	0.12	0.94
Flows (m^3 s^{-1})					
St. Marys River	2217	2256	403	507	0.49
St. Clair River	5743	5680	494	238	0.89
Detroit River	5904	5878	468	225	0.88
Niagara River	6761	6414	460	426	0.85
St. Lawrence River	8091	7735	833	535	0.88

[a] Historical Lake Michigan-Huron levels are arithmetic averages of Lake Michigan and Lake Huron levels.

models is limited to only the recent past. Table II provides statistics on levels and flows over 1973–1980 and suggests that the integrated models adequately represent the Great Lakes system. Some of the differences shown by Table II directly reflect errors in modeling net basin supplies that are discussed by Croley (1989). Other differences result from the use of constant, rather than actual, diversion rates and uncertainties in Niagara River flows discussed previously. In addition, the low correlation between historical and modeled St. Marys River flows reflects that Lake Superior has been regulated under Plan 1977 only since October 1979; the previous regulation plan did not consider Lake Michigan-Huron levels.

3. Lake Level Impacts

3.1. *Steady-State Scenarios*

Steady-state behaviors of the net basin supplies, lake inflows (inflows from the immediate upstream lake through the connecting channel), lake outflows, and lake levels are exemplified by Figure 1 for the Lake Erie basin for the GISS and base case comparisons. Table III summarizes impacts for all lakes and all climate change scenarios. Each scenario assumes unchanging diversions and consumptive uses, and the GISS and OSU scenarios assume no changes in Lake Superior regulation operations. For all lakes except Lake Superior (which has no upstream lake), connecting channel inflows and outflows comprise a large part of the water budget and drops in inflows are accompanied by even larger drops in outflows. However, reductions in outflows only partly offset the combined drops in connecting channel inflows and net basin supplies. For example, Table III shows that Lake Erie's aver-

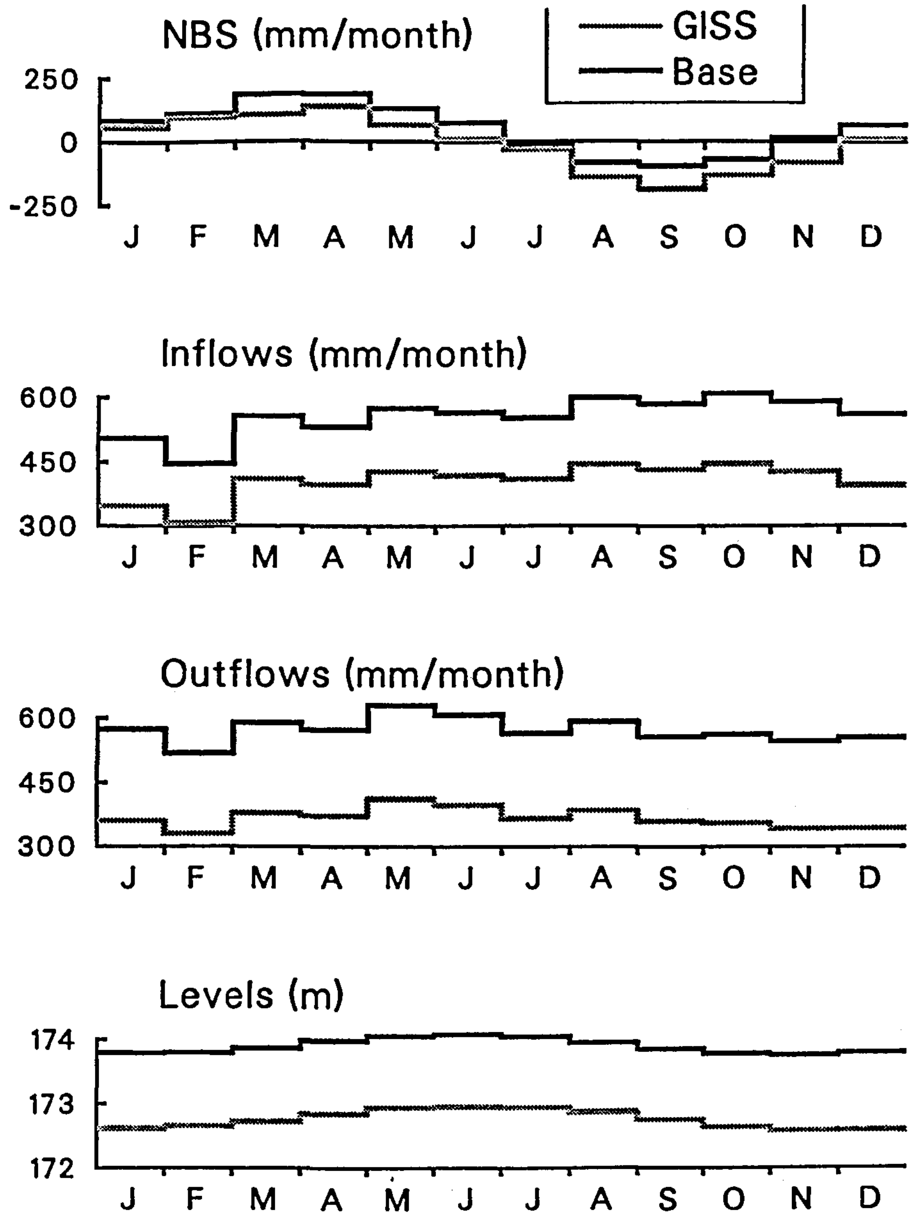

Fig. 1. Steady-state GISS Lake Erie lake level model outputs.

age GISS steady-state inflow minus its outflow rises 656 mm (compared to the drop in net basin supplies of 671 mm) while lake levels drop about 1.16 m.

Some of the planned results were not obtainable because of failure of the regulation plans under the climate change scenarios. As earlier climate change and consumptive use studies by others have found, the Lake Ontario regulation plan's mathematical algorithms behave erratically under extreme low water supply conditions that are insufficient to maintain both Lake Ontario levels and St. Lawrence River flows within the ranges specified by the regulation rules (F. H. Quinn, GLERL, personal communication, 1988; C. Southam, Environment Canada, personal communication, 1988). Under these conditions, Plan 1958-D typically attempts to maintain Lake Ontario levels by requiring negative outflows, an impossibility. No attempt was made to determine what Lake Ontario levels might be for the three scenarios; the lake's small size relative to the other lakes (enabling a greater degree of control of levels) and its lack of influence on the upper lakes means that a wide range of alternative regulation strategies are possible, including storing and releasing water over periods extending beyond the annual cycle.

The GFDL scenario produced such low water supplies to Lakes Superior and Michigan-Huron that the rule curves of the Lake Superior regulation plan failed as well. Within Plan 1977, the balancing equation becomes mathematically meaningless when Lake Superior's levels fall too low. To assess possible system behavior under the GFDL scenario, an alternative regulation strategy was assumed, one which essentially reflects historical operations by precluding long-term storage of net basin supplies or mining of the lake's water. Thus, for the GFDL scenario, Lake Superior outflows were taken equal to Lake Superior net supplies and other inputs (e.g., Long Lac diversions) on an annual basis. This is suitable for long periods (actual Lake Superior net basin supplies plus diversions differ from the St. Marys River outflows by less than 1% over 1951–80) and, for the 30-year period used herein, gives an estimation of long-term differences in lake levels for the downstream lakes.

The lake levels drop more under the GFDL and GISS scenarios than under the OSU scenario because of their much larger decreases in net basin supplies to all lakes but Superior than is observed under the OSU scenario. Lake Superior drops more under the OSU scenario due to larger decreases in net basin supplies than in the GISS scenario, as discussed by Croley (1990). GFDL has smaller drops in net basin supplies than GISS for Lakes Huron, St. Clair, Erie, and Ontario yet larger drops in the water levels on these lakes because of its larger drop in net basin supplies to Lakes Superior and Michigan which affect inflows to lower lakes and offset the reduced drops in net basin supplies there. Because the GISS scenario shows larger drops in net basin supplies on the remaining downstream lakes than the GFDL and OSU scenarios, the drops in lake levels in Table III under the three scenarios approach each other somewhat on the downstream lakes. The lake levels drop 40 to 130 cm for the GISS scenario, 190 to 250 cm for the GFDL scenario, and 50 to 100 cm for the OSU scenario.

3.2. *Transient-State Scenarios*

One transient scenario was supplied by EPA and used with the integrated models, representing the transition from the present climate to near the $2 \times CO_2$ climate

TABLE III: Average annual steady-state net basin supply, flows, and lake level differences

	Net basin supply[a] (mm)[c]			Inflow[b] (mm)[c]		
Lake	GISS	GFDL	OSU	GISS	GFDL	OSU
Superior	−16	−479	−163	–	–	–
Michigan-Huron	−399	−441	−210	−10	–	−113
St. Clair[d]	−2219	−1252	−1102	−40628	–	−32892
Erie	−671	−540	−331	−1857	–	−1473
Ontario	−844	−564	−210	−3407	–	−2432

	Lake outflow (mm)[c]			Lake level (m)		
Lake	GISS	GFDL	OSU	GISS	GFDL	OSU
Superior	−14	–	−162	−0.46	–	−0.47
Michigan-Huron	−386	–	−312	−1.31	−2.48	−0.99
St. Clair[d]	−42831	–	−33980	−1.21	−2.12	−0.87
Erie	−2513	–	−1794	−1.16	−1.91	−0.79
Ontario	–	–	–	–	–	–

[a] Adapted from Croley (1990).
[b] Inflows from the immediate upstream lake through the connecting channel. Note Lake Superior has no upstream lake and thus no inflow in this table.
[c] Expressed as a depth over the lake.
[d] Lake St. Clair inflows and outflows are relatively large since it is such a small lake.

during the period 1981–2060. Beginning with actual lake levels on 1 January 1988, the 80-year sequences of net basin supplies derived by Croley (1990) were used with the system model to determine lake level impacts. As Croley (1990) points out, there are serious difficulties in analyzing transient impacts of climate change with short historical data sets. The differencing approach described by Croley is used herein as well to give an idea of trends in climate change impacts that eliminate the effect of repetitive natural climate variations that otherwise would dominate the scenario comparisons.

Table IV shows that net basin supplies are highly variable but generally drop on all lakes except Superior. These changes in net basin supplies are reflected in changes in outflows and lake levels. The increased net basin supplies to Lake Superior are more than offset by increases in outflows which result in a small decline in Lake Superior levels of about 13 mm/decade. This is a consequence of the Lake Superior regulation plan which endeavors to balance water levels on Lakes Superior, Michigan, and Huron about their long-term mean values. The associated rise in the combined Michigan and Huron inflows (Lake Superior outflows) allows their annual outflows in Table IV to drop only 31 mm/decade; their combined net basin supplies drop more causing lake levels to fall about 59 mm/decade. On the other lakes, there are drops in net basin supplies, outflows, and lake levels; Lake St. Clair drops about 64 mm/decade, while Lake Erie drops about 66 mm/decade,

TABLE IV: GISS transient changes summary (mm/decade)[a]

Lake	Annual net basin supply	Annual net outflow	Lake level
Superior	+17	+20	−13
Michigan-Huron	−34	−31	−59
St. Clair	−245	−241	−64
Erie	−75	−70	−66
Ontario	−75	−57[b]	−93[b]

[a] Expressed as a depth over the lake.
[b] Computed over the first 7 decades since the Ontario regulation plan fails in the eighth.

and Lake Ontario drops about 93 mm/decade. Only the first seven decades were used in computing the average decadal difference in outflows and lake levels for Lake Ontario since the regulation plan failed (as in the steady-state scenarios) in the eighth decade. Note that while there are similar patterns in the behavior of the lake levels between this transient analysis and the GISS steady-state analysis (see Table III), the magnitudes of the drops are dissimilar (while of the same general order of magnitude).

4. Implications of Results

Climate change has the potential to alter many traditional activities in the Great Lakes region. Although changes in lake levels have major implications for Great Lakes users, altered precipitation, evaporation, and runoff patterns, presented by Croley (1990), will be important as well. Potential consequences of the altered hydrometeorologic patterns reported by Croley are discussed herein in addition to the implications of lake level impacts. Although environmental and socioeconomic consequences are addressed separately, these concerns are often intimately intertwined, since a healthy ecosystem is vital for the social or economic wellbeing of a number of interests (e.g., riparian, commercial fishing, recreation, commercial interests) and some issues (e.g., disposal of toxic dredge spoil) combine environmental, social, and economic dimensions.

4.1. *Environmental Implications*

Lowering of Great Lakes levels could dramatically affect the Great Lakes' ecosystem production through dependence on the consistent availability of marshes and wetlands that serve as breeding and nursery areas for fish and wildlife. Even a 20 cm lowering of Lake Michigan-Huron levels could affect 64% of all Great Lakes wetlands in the U.S. (Manny, 1984). Although confined wetlands may be especially vulnerable to disruption from lake level declines (Wall, 1988) even open shoreline wetland extents could be permanently reduced due to their direct lake level dependence, unsuitable offshore substrates, and steep offshore drop offs, combined with a resulting reduction in seeds and rhizomes for colonization (Manny, 1984). On the other hand, the total areas of different wetland types may remain nearly unchanged if water levels drop so slowly that the shoreline can adapt (Meisner *et al.*, 1987). Decreased wetland extents could significantly reduce Great Lakes fisheries production, even in deeper waters; over half of all Great Lakes fish species use wetlands for spawning and nursery habitat (Goodyear *et al.*, 1982).

Increased water temperatures may result in substantial changes in the Great Lakes ecosystem. With water temperatures remaining above 4 °C throughout the year, buoyancy-induced turnovers in the fall and spring may not occur. Without turnover, hypolimnion chemistry may be altered; oxygen may be depleted, releasing nutrients and metals from lake sediments. On the other hand, the lakes may experience single winter turnovers (routinely or sporadically) even with water temperatures above 4 °C, if temperature gradients are small and winds are strong enough to induce turbulent mixing (Hutchinson, 1957). Meisner *et al.* (1987) provide an initial assessment of the potential impacts of increased water temperatures on Great Lakes fishes (potential changes in the lakes' turnover regimes are not considered). Among their general expectations are northward shifts in the geographical distribution of warm and cold water species, changes in relative abundance of species within fish communities, and changes in yields of different species. Table V summarizes some of these anticipated impacts.

TABLE V: Anticipated impacts of increased water temperatures on selected Great Lakes basin fishes[a]

Species	Impacts
smallmouth bass largemouth bass bigmouth buffalo	– northward extension of range
lake trout lake whitefish	– northward contraction of range
brook trout	– contraction of range to stream head waters – reduced populations due to competition with other trout for remaining habitat
whitefish yellow perch (south) walleye (south)	– decreased populations due to increased egg and larval mortality or inhibited reproduction
alewife yellow perch (north) walleye (north)	– increased populations due to increased reproduction and reduced mortality
lake whitefish northern pike walleye	– decreased sustainable yield

[a] From Meisner *et al.* (1987).

4.2. *Socioeconomic Implications*

Power Production

The waters of the Great Lakes are extensively used for hydropower production. Facilities range from low-head plants on the St. Marys River to high-head facilities in the Niagara and St. Lawrence Rivers. A climatic warming would result in decreased flows and water-surface elevations which would contribute to lower hydropower production. Record low levels and flows in the 1960s, while less severe than the climate change scenarios, resulted in hydropower production losses of 19–26% on the Niagara and St. Lawrence Rivers (Allsop *et al.*, 1981). Such losses could be especially important since hydropower is inexpensive and nonpolluting when compared to the primary alternatives, fossil fuel or nuclear power facilities. Coal-fired power plants additionally require the economic efficiencies provided by waterborne transportation of coal; with lower water levels, higher transportation costs would directly affect power production costs.

The full impact of climate change on power production interests depends not only on the water supplies available for hydropower, cooling, or transportation, but on the changes in peak power demands that result from the increased air temperatures. In much of the U.S. portion of the Great Lakes basin, peak power demands occur in the summertime for cooling (R. Crissman, New York Power Authority, personal communication, 1988); climatic warming could increase peak power demands, making the loss of hydropower production even more critical. On the other hand, climatic warming may substantially reduce the peak power demands for winter heating that occur in Canada, making replacement of hydropower facilities nonproblematic (J. Eaton, Ontario Hydro, personal communication, 1988). Impacts on peak power demands are difficult to predict since they are so closely tied to population levels, and continued growth in the use of air conditioners in Canada could raise summer peak demands above winter levels.

Navigation

The Great Lakes/St. Lawrence Seaway is a major freshwater transportation system. This system depends upon adequate depths in the connecting channels and harbors to function at full capacity. During conditions of low levels, more trips must be made to move the same amount of cargo; this increases shipping costs and the increased traffic could cause backups at recognized bottlenecks in the system (e.g., Welland Canal). On the other hand, a decreased ice season could lead to an extension of the current navigation season, contributing to better vessel utilization and a decrease in stockpiling. Any impacts on the shipping industry will have direct effects on industries that depend upon the Great Lakes for transport of production inputs or final products (e.g., iron, steel, grain).

Shipping interests suggest that industry contraction in the 1960s was related to the record low water levels of that period (Marchand *et al.*, 1988). Under the climate change scenarios, those low levels will be typical. Climate change impacts climate change, if it occurs as expected, will lead to a lowering of Great Lakes water levels and connecting channel flows. The average steady-state lake levels are seen to drop between ½ to 1⅓ m for the GISS $2 \times CO_2$ climate scenario, drop 2 to 2½ m for the GFDL scenario, and drop ½ to 1 m for the OSU scenario. Analyses of the GISS 80-year transient scenario indicate that the lakes would drop between 13–93 mm/decade on average. The Lake Ontario regulation plan fails in all steady-state and transient climate change analyses, reflecting its design for regulation within present ranges of Lake Ontario total water supplies and levels. The Lake Superior regulation plan fails under the GFDL steady-state scenario.

The climate change effects modeled herein will require new paradigms in water management in the Great Lakes Basin. Allocation conflicts between users of the Great Lakes will likely result. Lowered lake levels could produce large reductions in wetland areas and lower hydropower production. While reduced lake ice formation could lengthen the shipping season, lower lake levels could also increase waterborne shipping costs via lower vessel load limits, traffic backups at the Welland Canal and Sault Ste. Marie, and dredging of sediments highly contaminated with toxics. Dredging and disposal of toxic-contaminated harbor sediments may pose critical problems for municipal and private marinas and create conflicts between the many governments having jurisdiction over the lakes. To manage potential allocation conflicts, the Boundary Waters Treaty of 1909 may have to be modified to consider commercial, industrial, riparian, recreational, and ecological interests in addition to presently considered domestic and sanitary water supply, navigation, hydropower, and irrigation interests. The Lake Superior and Ontario regulation plans would require revision to handle persistently low water supplies. Additional work is anticipated to determine the potential to minimize the hydrologic impacts of climate change via alternative regulation strategies, each of which will require tradeoffs between lake levels and connecting channel flows and between the upper and lower lakes.

Low confidence in the GCM outputs and subsequent lake level estimates is probably a major obstacle to long-term contingency planning. In addition, other factors that are difficult to predict (e.g., economic, demographic, technological) are certain to complicate policy development. Although these climate change scenarios are highly uncertain, they highlight the need for policies to increase the region's resiliency to climatologic uncertainty. Policies that protect the quality of existing water supplies, encourage efficient use of existing supplies, and adequately address present allocation conflicts will provide advantages for future water management even if climate changes fail to materialize as expected.

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